POTENTIAL FOR THE APPLICATION OF DYNAMIC SKIN THERMOGRAPHY AFTER LOCAL HYPOTHERMIA

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Abstract

Infrared thermography is one of the widely used non-invasive diagnostic methods. While the procedure is mainly used for early malignant tumor diagnostics, a potential application for thermography was proposed in cardiovascular, skin, autoimmune diseases, arthritis, Reynaud's syndrome, burns, surgery and therapeutic treatment monitoring. The method of thermographic evaluation has not changed significantly since the end of 20th century. In this study we attempted to characterize the influence of skin capillary blood flow on surface temperature recuperation following local hypothermia. To improve sensitivity and standardize the procedure we developed a study protocol that involves minimizing or excluding the influence of external factors on study results. An original applicator was used to apply dosed hypothermia. Massive porcine tissue block was chosen as a passive model without active heat and mass transfer but with heat capacity, structure and heat dissipation characteristics similar to human tissues. 51 healthy volunteers were assigned to control group, while 16 patients with diabetes mellitus constituted the main study group. Cumulative temperature difference was calculated in all cases. It was 121,8 ± 70,8 °C×s in the control group, 95,6 ± 54,4 °C×s in the main study group and 307,2 ± 43,4 °C×s in the passive model. Based on the study results, we made the following conclusions: absence of heat and mass transfer in the passive model complicates heat balance recuperation due to layered structure of the skin; heat balance recuperation curve is an individual parameter and is not influenced by age or gender.

Keywords: thermography, contactless dynamic thermography, thermal imaging device, cold test applicator, isothermic chamber, diabetes mellitus, skin capillary blood flow.

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ПОТЕНЦИАЛ ПРИМЕНЕНИЯ ДИНАМИЧЕСКОЙ ТЕРМОГРАФИИ КОЖИ ПОСЛЕ ЛОКАЛЬНОЙ ГИПОТЕРМИИ

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Резюме

Метод дистанционной инфракрасной термографии – один из неинвазивных диагностических методов, широко применяемых в медицине. Помимо применения для ранней диагностики злокачественных новообразований было предложено его использование при сосудистых заболеваниях, кожных болезнях, ревматических заболеваниях, артритах, синдроме Рейно, ожогах, хирургии, мониторинге эффективности терапевтического лечения и др. Необходимо отметить, что с конца прошлого столетия технический уровень выполнения тестов существенно не менялся. В своей работе мы попытались охарактеризовать вклад капилляров системы кровоснабжения кожи в динамику восстановления температуры поверхности после локальной гипотермии. Для повышения чувствительности и стандартизации метода мы разработали протокол исследования, предполагающий максимальную стандартизацию условий внешней среды или исключение их влияния. Для дозированной локальной холодовой нагрузки использовали оригинальный аппликатор. В качестве пассивной тепловой модели с отсутствием активного тепломассопереноса, но с близкими к человеческим тканям свойствами теплоемкости, структурой и характером кондуктивного перераспределения тепла, была выбрана модель на основе массивного блока тканей свиньи. Группу контроля составили условно здоровые добровольцы. В группу контроля вошли 51 человека, в группу больных диабетом II типа –16 человек. Нами получены показатели интегральной разницы температур. Показатель интегральной разницы температур здорового человека составил 121,8 ± 70,8 °C×с, пассивной модели – 307,2 ± 43,4 °C×с, больного сахарным диабетом – 95,6 ± 54,4 °C×с. Были сделаны следующие выводы: отсутствие тепломассопереноса в пассивной модели усложняет восстановление теплового баланса в виду многослойного строения кожи; кривая восстановления теплового баланса индивидуальна и не зависит от пола и возраста.

Ключевые слова: термография, бесконтактная динамическая термография, тепловизор, аппликатор для проведения холодовой пробы, изотермическая камера, сахарный диабет II типа, капиллярное кровообращение кожи.

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Introduction

Noninvasive infrared thermography is one of the widely used diagnostic methods. The first practical application of diagnostic thermography was proposed in 1957 by R. Lawson, who discovered that skin temperature in the area of a breast tumor is higher than the temperature of the normal tissue [1]. In addition to its application for the early diagnosis of malignant tumors, its use was also suggested for vascular diseases (diabetes mellitus, thrombosis), skin diseases, rheumatic diseases, arthritis, Raynaud syndrome, burns, surgery, monitoring of the therapeutic treatment efficacy, etc [2–5]. It should be noted that since the end of the last century the technical level of tests has not changed significantly.

Currently almost all known varieties of thermographic diagnostics evaluate condition of tissues and organs that project their heat-generating properties onto the skin and mucosa surface directly above them. The use of thermography in diabetes mellitus, where the measurements of heat generation are aimed at identifying significant systemic disorders of innervation and blood circulation seems to be an exception [6, 7].

Diagnostic thermography in diabetes mellitus is an example of a potential application of local thermographic measurements for monitoring the development of various system level changes. Changes in the regulation of skin capillaries or their systemic degradation will evidently be reflected in the temperature fluctuations of any arbitrary local surface area of the body.

We assumed that creation of a new method of dynamic thermal evaluation, limited in depth to evaluate heat exchange in the skin no deeper than the layer of subcutaneous tissue, would significantly increase the sensitivity of thermography to changes of cutaneous microcirculation. An increase in sensitivity along with a strict standardization of test conditions may be sufficient to assess subtle changes in systemic capillary status.

Aim: to assess the contribution of the capillaries of the skin blood supply system to the dynamics of surface temperature recovery after local hypothermia.

Materials and methods

Room for thermographic research

When conducting dynamic thermography, in contrast to static measurements, external short-period temperature fluctuations introduce significant interference. To reduce the effect of external temperature fluctuations associated with convection turbulence, thermography was carried out in a room with a laminar air exchange system (fig. 1). The air inflow was provided through laminar nozzles by the air supply unit with the "Breezart 1000 lux" electric heater (Brizart LLC, Russia), and the outflow was executed from a low point using a BP-86–77–2.5 exhaust system (Zavod Musson LLC, Russia). The thermosetter of the air handling unit provided a constant temperature of 24 ± 0.25 °C. The measurements were carried out at an atmospheric pressure of 746 ± 10 mm Hg.

Isothermal chamber

The isothermal chamber was constructed to eliminate thermal range reflections from the surrounding objects on the surface of the skin. The size of the chamber was 50×50×190 cm. It was covered on the inside with a carbon dyed heat-absorbing material.

Applicator for dosed local hypothermia

The local cold test was performed using an original applicator, which is a polymer cylindrical hollow body, one of the ends of which is hermetically sealed with a 12.5 mm aluminum plate (fig. 2). Deionized water (endothermic phase transition at 0 °C) in a volume of 2 ml served as the working medium ensuring the constancy of the applicator surface temperature. Efficient heat transfer from the aluminum plate (working surface of the applicator) to the working medium was provided by the aluminum core. Prior to the test the applicator was cooled to a temperature of -18 °C, and then under the thermographic control it was heated until the surface

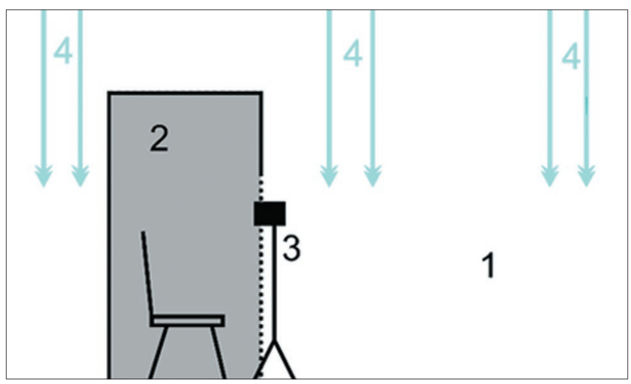

Fig. 1. Diagram of an isothermal chamber and a room for research (1 – room for thermographic research; 2 – isothermal chamber; 3 – infrared camera on tripod; 4 – air flow direction)
Рис. 1. Схематическое изображение изотермальной камеры и опытной комнаты (1 – комната для тепловых исследований; 2 – изотермальная камера; 3 – инфракрасная камера на штативе; 4 – направление воздушных потоков)

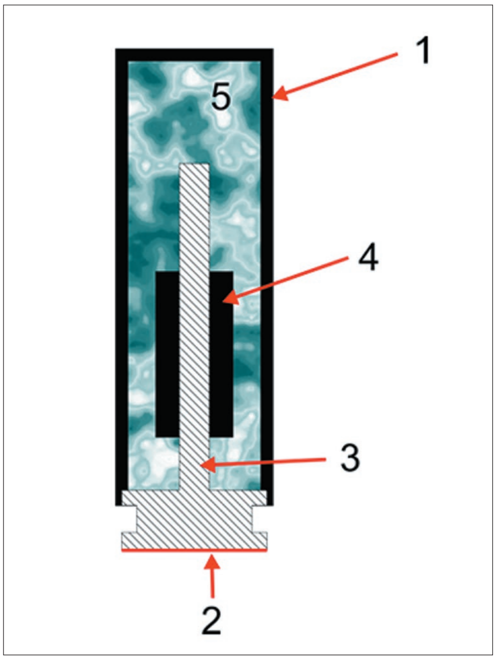

Fig. 2. Cold test applicator design (1 – polymer cylindric body; 2 – working surface of the applicator (12.5 mm aluminum plate); 3 – aluminum core; 4 – silver coupling mounted on the aluminum core; 5 – working medium (2 ml deionized water))
Рис. 2. Схема устройства аппликатора «холодного» теста (1 – полимерная оболочка в форме цилиндра; 2 – рабочая поверхность аппликатора (12,5 мм алюминиевая пробка); 3 – алюминиевая сердцевина; 4 – серебряная муфта, установленная на алюминиевую сердцевину); 5 – рабочая среда (2 мл деионизированной воды))

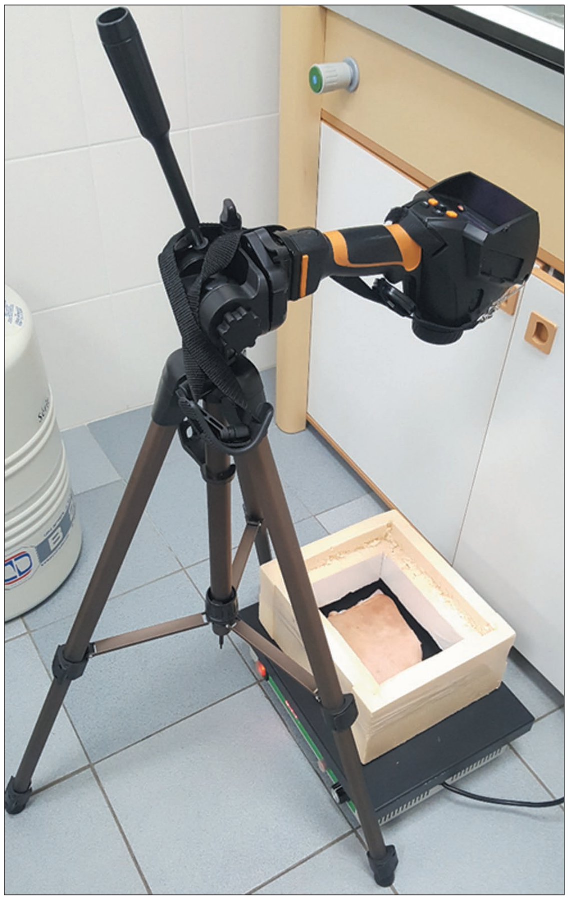

Fig. 3. Thermographic evaluation of the passive model
Рис. 3. Процесс тепловой оценки пассивной модели

temperature reached 0 °C. The temperature "jerk" at the moment of application, associated with the limited rate of heat transfer in water, was largely compensated for by silver coupling (Ag 99.9%) tightly mounted on the core.

Infrared camera

Testo 875 (Testo SE &Co. KGaA, Germany) infrared camera was used in the current study.

Image Quality: 160x120 pixel matrix, with thermographic image resolution of 320 × 240 and the spectral range of 8–14 μm. The study was conducted using a dynamic temperature scale with automatic recognition of a hot/cold point. Temperature resolution was 0.1°C.

Passive model of skin heat dynamics

A single porcine tissue block was chosen to be a passive model in our study with no active heat and mass transfer, but with heat capacity properties, structure and nature of conductive heat redistribution close to human tissues. A block of tissues measuring 20 × 25 × 6.5 cm included the epidermis, dermis, subcutaneous fat and muscle tissue. Bone and cartilaginous tissues were absent.

In the experiment the block was placed on the Ecros ES-HF3040 laboratory heating surface (Ekros-Analytika LLC, Russia), with a given surface temperature of 41 °C. To reduce heat loss in the lateral directions, the block was placed in a frame of foamed polyurethane (fig. 3). Dynamic thermographic measurements of the passive model were carried out after thermal balance between the passive model surface and the environment was reached.

A group of healthy volunteers

51 healthy volunteers (16 male and 35 female) aged between 21 to 89 took part in the study. Information about related diagnoses was registered according to medical records. Exclusion criteria were diseases of the cardiovascular system: hypertension, coronary heart disease, atherosclerosis, rheumatic heart diseases, and also diabetes mellitus type I and II.

A group of diabetes mellitus patients

16 patients with type 2 diabetes mellitus (10 male and 6 female) aged between 37 to 84 years were enlisted in the study. The presence of diabetes complications, such as renal failure, heart failure and ocular manifestations of diabetes, as well as duration of the disease and surgical interventions (microinvasive vitrectomy, panretinal laser coagulation) were noted based on medical records.

Pre-study adaptation

All subjects didn't receive any vasoactive drugs at least for 24 hours before the study. On the day the subjects were banned from drinking coffee, tea and smoking. The movement of a person into a room equipped for thermography was carried out in such a mode that the subject avoided noticeable loads on the cardiovascular system in accordance with his age and somatic condition. Given the insignificant temperature difference between the conditions of a thermostatically controlled room for thermographic research and other rooms of the institute, a rational pre-study adaptation time was 15 minutes. The timing of adaptation was selected on the basis of temperature stabilization of the passive model after 10–12 minute adaptation after transportation from an arbitrary room to a room for thermographic studies.

Data acquisition protocol

In the study of human skin temperature, the thermal imager was mounted horizontally on a tripod at a height of 110 cm from the floor directly at the entrance to the isothermal chamber. After initial thermographic evaluation the cold test applicator was put to the inferior zygomatic bone margin area for 20 seconds. The study area was chosen due to ease of access, high blood vessel density and a sufficiently long distance from organs that may interfere with the results of infrared imaging (e.g. air flow during respiration). Thermographic images were acquired each 20 seconds for 5 minutes following applicator removal. Immediately after this, similar manipulations were performed on the inferior zygomatic bone margin area on the other side.

During porcine tissue block evaluation, the infrared camera was installed vertically above the study surface. The applicator was put to the skin in the central part of the block surface. Image capturing mode, application time and thermogram recording intervals were the same.

Data processing

Thermographic images were processed and analyzed using specialized IR Soft program (version 3.1sp3). The lowest temperature in local hypothermia zone was acquired using the program (fig. 4).

After image processing empiric temperature recovery diagrams were drawn based on minimal recorded temperature in cold application zone.

According to the basic idea of trying to evaluate the active and passive components that determine heating of a skin surface area after local cooling, it became necessary to choose a smooth temperature recovery function. In further calculations, we took into account temperature fluctuations with respect to the smooth recovery curve, which is set parametrically, not absolute temperature values. As a similar basic curve, the logarithmic function of temperature recovery was reconstructed using the least square method for each test. The choice of the logarithmic law as the basis of the approximating function was motivated by its highest affinity for the obtained recovery temperatures when studying a passive model of pig tissue. Initially, when choosing the "basic" law, we compared all the options of nonlinear functions offered by SPSS Statistics (quadratic, cubic, power, logarithmic, exponential, etc.). When describing the temperature recovery curve of the passive model, the logarithmic function showed maximum determination coefficient R2 (the dispersion fraction of the dependent variable Y, specified by the predictor X).

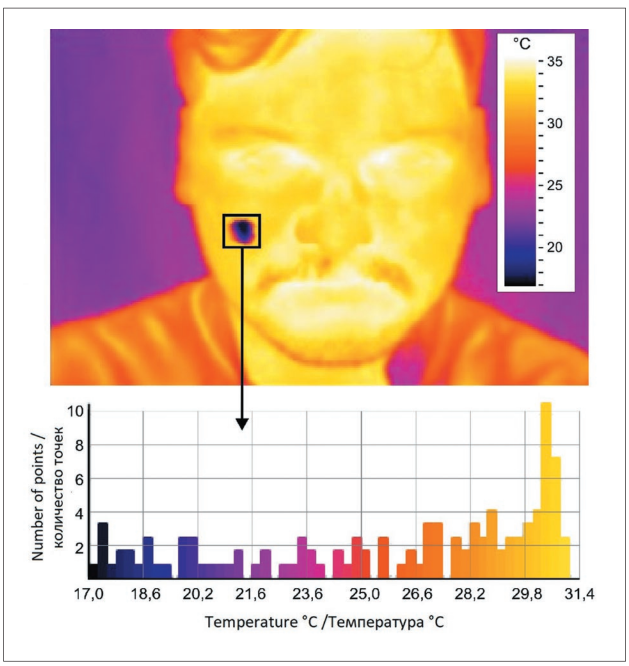

Fig. 4. Minimal temperature detection in cold application zone. A thermal image acquired using Testo 875 software and color reference for interpretation are shown above. Cooled zone is visible on the patient's right cheek after cold application. This area is cooler (marked with blue color) compared to surrounding tissues. Temperature distribution for the highlighted area is presented in the lower part of the picture. Minimal detected temperature in this area is used for all following calculations

Рис. 4. Измерение минимальной температуры в пределах предварительно охлажденного участка кожи. Сверху – полученная с помощью программного обеспечения Testo 875 термограмма поверхности лица и цветовая легенда для ее интерпретации. На правой щеке пациента видна локальная охлажденная зона, образовавшаяся после контакта с апликатором. Относительно окружающих тканей, зона охлаждена (маркируется синим цветом). Для области выделенной прямоугольником на термограмме, в нижней части рисунка показано распределение температур. Для дальнейших вычислений была использована минимальная температура, обнаруженная в этой зоне

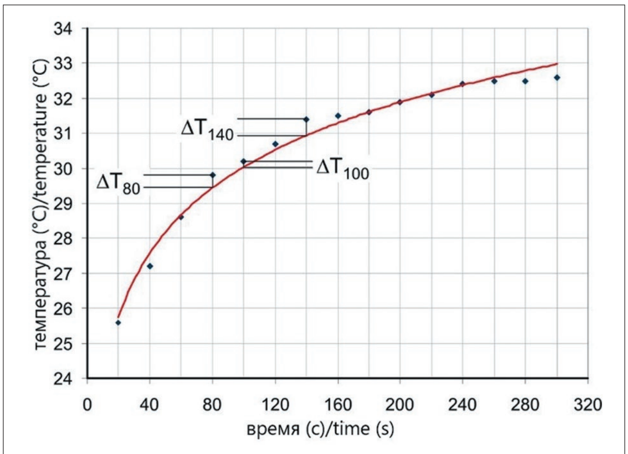

Fig. 5. Example of instantaneous deviations of the actual surface temperature recovery from the logarithmic trend
Рис. 5. Пример мгновенных отклонений реальной кривой восстановления температуры от логарифмического тренда

Thus, a logarithmic regression was individually calculated for each patient and passive model test, according to which the remainder modulus was calculated (fig. 5) for each point of the time axis with an interval of 20 seconds. Then the total parameter ∑ΔT characterizing these residues was calculated. The real temperature and its dynamics, approximated by the logarithmic law, made it possible to calculate the temperature deviation from the "ideal" restoration of the thermal balance of the surface (fig. 5). To exclude the dependence of the temperature beat volume on the fractionality of observations, the sum of these deviations was multiplied by the time between measurements: $\int\Delta T = \sum\Delta T \times t$ (°C × s). The presented indicator was conditionally called by us "cumulative temperature difference".

Statistical analysis was conducted using IBM SPSS Statistics 21 software package.

We used the nonparametric Mann-Whitney test to compare independent samples, given that the ∫ΔT distribution is different from the normal distribution for comparing groups by this indicator.

Results

Mean ∫ΔT value for thermographic evaluation of porcine tissue block passive model was 307.2 ±43.4 °C×s.

∫ΔT was significantly lower in the healthy volunteer study group (121.8±70.8 °C×s). High individual convergence of measurements was revealed for each person. At the same time, it was found out that the individual contralateral discrepancy ∫ΔT did not exceed 18%, and the discrepancy in a series of repetitions in a day time or more did not exceed 19%. There were no statistically gender or age-dependent significant differences in ∫ΔT. Similarly, no correlation was revealed between ∫ΔT and cardiovascular system disorders (hypertension, coronary heart disease, atherosclerosis, rheumatic heart diseases).

Table
Cumulative temperature difference (∫ΔT) in healthy individuals, in the passive model and in people with diabetes
Таблица
Интегральная разница температур (∫ΔT) у здоровых лиц, в пассивной модели и у лиц больных диабетом

Group Группа	Number of patients/cases Число пациентов/случаев	∫ΔT, °C×s ∫ΔT, °C×c
Healthy volunteers Здоровые добровольцы	51	121,8±70,8*
Passive model Пассивная модель	5	307,2±43,4
Diabetes mellitus Больные диабетом II типа	16	95,6±54,4*

Data expressed as mean (M) ± standard deviation (SD)
* difference in groups p=0,021
∫ΔT – cumulative temperature difference
Результаты представлены в виде среднего значения (M) ± стандартное отклонение (SD)
* разница в группах p=0.021
∫ΔT – интегральная разница температуры

The group of patients with verified diabetes showed statistically lower values of 95.6 ± 54.4 °C×s compared with the group of conditionally healthy people in contrast to the passive model, which demonstrated overestimated ∫ΔT index.

Discussion

In the current study we attempted to characterize individual systemic features of a human capillary network by means of a thermographic evaluation using dynamic thermography.

It is obvious that active heat and mass transfer facilitated by the capillary network in the epithelial tissues will influence the heat production of each surface area. This generally contributes to a static thermal balance value, which is a constant surface temperature in the given conditions.

Human tissues in direct contact with the environment play virtually no part in heat generation. They receive excess heat from internal organs, functioning as a kind of radiator, since it is the cover tissues that are most involved in heat removal process [8, 9]. Under conditions of room temperature (21–23°C) and relative humidity of 40–60%, the greatest amount of heat is removed from the body through radiation, i.e. in the form of infrared ray generation from the body surface [10]. There are many attempts to use static temperature indicators to assess the condition of both the underlying internal organs and the network of blood vessels actively transferring heat from them to the surface [1–5].

Dynamic measurements aimed at evaluating local vessel conditions are also known. In these measurements vessel reactions were assessed mainly using cold test. I. Mizeva et al. [11] studied the relationship between blood flow and skin surface temperature during cold test using simultaneous thermometry and laser Doppler flowmetry (LDF). The authors sugggested 2 mechanisms for vascular reaction change based on LDF results the first mechanism is the rapid change in skin thermal conductivity associated with a decrease in "recruited" capillaries, and the second mechanism is a decrease in the force of temperature effects caused by constriction of arterioles and redirection of blood into arteriovenous anastomoses. However, no correlation between skin surface temperature deviation and LDF data was observed during cold test.

M. Davey et al. [12] questioned the hypothesis about the effect of skin blood flow on cold test results. The authors attempted to assess the influence of skin blood flow on the change in skin surface temperature in subjects not suffering from cold injury by comparing the change in blood flow during a cold test on a perfused and non-perfused foot. These results were compared with those of patients diagnosed with non-freezing cold injury. Based on the thermographic and LDF data they acquired the authors made a conclusion that any difference in skin surface temperature between the study groups was determined exclusively by the effect of blood flow.

All of the mentioned studies confirm the connection between the local and regional metabolism and the surface thermal dynamics. But at the same time, the question remains: does the nature of temperature recovery after local surface hypothermia bear information about subtle changes in the status of capillaries at the system level? We assumed that the weak thermal response of the local skin capillaries can be assessed by a detailed observation of the dynamics of temperature recovery after dosed cooling of the local surface area.

At the beginning of our work on the method development, we inaccurately assumed that hypothermia applied to a local area of the skin could trigger a sequence of regulatory reactions that intensify heat and mass transfer in the skin. These reactions will cause the temperature recovery curve to become more complicated. Properties of the temperature recovery curve became the main subject of our study.

To assess the dynamics of temperature recovery, an original applicator was developed, which not only can absorb a strictly dosed amount of heat, but also allows limiting the contact zone. A small area of the working surface of the applicator allows limiting the spread of the thermal front in the lateral direction and in depth for a short application time.

Using the example of a passive model of a block of porcine tissue, we attempted to give a thermographic characteristic of a tissue similar to the human tissue, but lacking active heat and mass transfer. As can be seen from the average values given in Table 1, the passive model is distinguished by a large deviation of the temperature curve from a smooth logarithmic function. At first glance the result may seem paradoxical – a more complex temperature recovery curve in the complete absence of the ability to control heat generation by the body – but it is explained by the layered structure of the epithelial tissues. Indeed, each of the layers of the skin and subcutaneous fatty tissue have sufficiently contrasting properties to create a complex passive thermal response to local hypothermia.

In these tissues both the heat capacity and the kinetic indices of conductive heat transfer are different, which gives the effect of the heat front lagging from different layers during restoration of temperature balance. In such a situation, the presence and activity of capillaries will smooth out the temperature response of the multipart structure, "mixing" the thermal response of the layers under observation and also allowing them to simultaneously cool down at the moment of cold application to the surface.

Normally, human skin also has a pronounced layered structure: the epidermis, dermis, and subcutaneous fatty tissue. Each of these layers has its own heat capacity and conductive properties. For this reason, skin structures that lack the ability to "mix" the temperature will produce a complex signal of the surface temperature recovery after contact with the cooled applicator has ceased.

To reduce the effect of thermal noise, standardization of physical conditions and an original infrared thermography protocol were proposed, which allowed to evaluate the effect of capillaries on the temperature recovery dynamics in a group of patients with well-studied pathology.

It is known that in patients with diabetes mellitus the capillaries of the skin are dilated. Such capillaries have a thick fibrotic basement membrane [13, 14]. This should affect the heat transfer within the skin layers, smoothing the effect of its layered structure, during temperature recovery after local hypothermia. The single measurements we carried out confirm this effect (see Table 1).

We believe that the proposed approach to dynamic thermography in combination with dosed local cold test, which allows to limit the thermal response of tissues to the depth of subcutaneous fatty tissue, gives much more information about capillary status than any other "global" tests.

Probably, in the future it will be necessary to move from the summation of the temperature difference between the real recovery curve and its mathematical model, which we have provided as examples for individual key points in time, to an integral description of a continuous process. But it will be rational after careful selection of the optimal approximation function of real data.

Conclusion

As a result of research (experiment), standardization of physical conditions and the original protocol of infra-

red thermography were proposed. An applicator for local dynamic thermography was created. The following conclusions were also made: the lack of heat and mass transfer in the passive model complicates the restoration of heat balance due to the multi-layered structure of the skin; the heat balance recovery curve is individual and does not depend on gender and age. We obtained the ∫ΔT indices of the integral temperature difference. The ∫ΔT indicator of a healthy person was 121.8±70.8°C×s; in the passive model it was 307.2 ±43.4°C×s; in diabetes it makes 95.6 ± 54.4°C×s. All the above results give the potential to use the method in medicine.

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